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A novel InAs quantum wire system

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Abstract

We report here a new technique in patterning high quality low-dimensional electrons in single InAs quantum wells. Grown by molecular beam epitaxy, the single InAs quantum well is sandwiched between AlSb barriers and capped by a thin layer of InAs. When the InAs cap layer is patterned by electron beam lithography and selectively removed, electrons are induced in the InAs quantum well below due to the different surface Fermi level pinning voltages on the exposed AlSb layer from the InAs cap. One-dimensional quantum wires can thus be conveniently defined by lithography and nm-shallow etching. We demonstrate that these one-dimensional electrons posses a long elastic mean free path (> 1.4 μm) and a long coherence length (> 3 μm) at 2 K.

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Keywords: Quantum wire; InAs; One-dimensional electrons; Surface Fermi level pinning

1. Introduction

To study quantum wires and quantum dots [1–3], it is desirable to have a sample system whose electronic properties can be well controlled. For example, if the quantum dots are to be used in single electron devices, a low number of electrons and a large energy separation between neighboring states are of interest. In the case of quantum wires, a single one-dimensional channel would be ideal. The most popular approach is using GaAs-based high electron mobility transistor structures with Schottky gates. Here we report an alternative nanofabrication scheme that has several advantages. The samples used for demonstrating this new approach are single InAs/AlSb quantum wells grown on GaAs by molecular beam epitaxy. A model structure has a thick AlSb/GaSb buffer, a 17 nm InAs quantum well, and a 25 nm AlSb top barrier. The samples are capped with three thin layers, InAs/AlSb/InAs, 3 nm each.

2. Experimental scheme

The fabrication process only involves electron-beam lithography for device pattering and shallow wet chemical etching for pattern transfer [4]. We use a focused electron beam to directly write patterns onto a positive tone electron beam resist PMMA. The written region is later washed away in the

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development process. The patterned PMMA is then used as the etch mask. We have developed highly selective etchants that can easily remove either InAs or AlSb and leave the other one intact.

The surface Fermi level pinning voltage for InAs is ∼0.15 eV above its conduction band minimum. For AlSb, it is roughly ∼0.8 eV above its valence band maximum. We take advantage of such a drastic difference in surface Fermi level pinning positions to define the electrons in the InAs quantum well.

As part of the fabrication scheme, the as-grown sample is intentionally designed to be non-conductive. This is accomplished by p-doping in the three cap layers along with the structure parameters and a relatively low Fermi level pinning at InAs surface. Based on a self-consistent band bending calculation, the resulting Fermi level lies ∼100 meV below the lowest InAs quantum well subband at 4 K. Hall measurements on as-grown samples confirm their insulating characteristic.

After 3 nm shallow etching, high mobility electrons are induced, forming a replica of the etched pattern. We have used magnetotransport on Hall bar fabricated using photolithography to characterize the concentration and mobility of two-dimensional electrons at 4 K. The electron concentration becomes 4.9×10^{11} cm^2 and the mobility is 2×10^5 cm^2/V s. The elastic mean free path is thus calculated to be 2.3 μm

We have further etched off the 3 nm AlSb near the surface. The exposed 3 nm InAs develops its surface Fermi level pinning position again at ∼ 0.15 eV above the conduction band minimum. The two-dimensional electron concentration in the InAs quantum well becomes nearly zero at 4.2 K.

To further test the validity of the design, we have etched off the second 3 nm InAs quantum well. Indeed, the induced electron concentration becomes 1.1×10^{12} cm^2 and the mobility is increased to 4.27×10^5 cm^2/V s. The corresponding elastic mean free path is calculated to be 7.0 μm. The finding of increased electron concentration, compared to the case where only the first 3 nm InAs is etched, is consistent with the design. The higher concentration is due to the thinner dielectric layer in between the InAs quantum well and the surface. In addition, the accompanied higher mobility is due to enhanced screening.

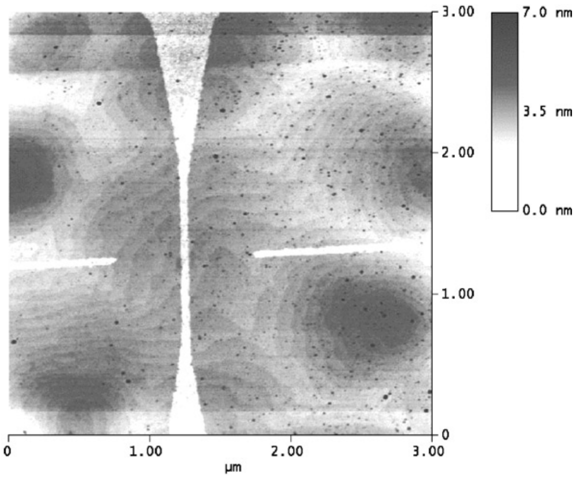

Fig. 1. Atomic force micrograph of a quantum point contact device. The conductance of the conducting channel (from top to bottom) is modulated by voltage bias applied to the two side gates. The surface of the wafer shows atomic terraces that are originated from the threading dislocations.

3. Nanofabrication results

This fabrication technique proves to be versatile for defining narrow quantum wires. Fig. 1 shows an atomic force micrograph of a quantum point contact. Other than the source and the drain, two side gates are defined by the same means. A conductive gate serves the purpose of modulating the electron concentration in the channel nearby. The non-uniformity of the lithography width is within several nanometers. The depth of the wet etching is verified to be consistent with the targeted thickness, 3 nm.

Fig. 2 shows the micrograph of a 300 nm diameter quantum ring. Note that the surface of the finished sample shows many bumpy features, approximately 2–3 nm in height and 20–30 nm in diameter. We attribute those to be the residue of PMMA molecules. when these residue molecules are fully dissolved by chemical solvents, atomic terraces are clearly revealed, as shown in Fig. 1. Single electron transistor structures are also fabricated by the same technique, and one example is demonstrated in Fig. 3.

The fabrication technique is versatile, as any pattern defined on the resist in principle can be transferred to the electron layer. Based on magnetotransport data taken from a series of Hall bars with different channel

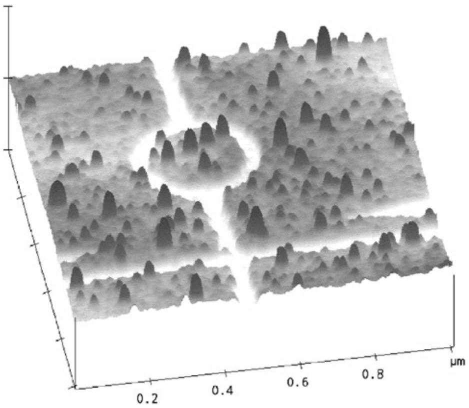

Fig. 2. Atomic force micrograph of a 300-diameter ring for probing the coherence of one-dimensional electrons. The vertical bar is 10 nm/division.

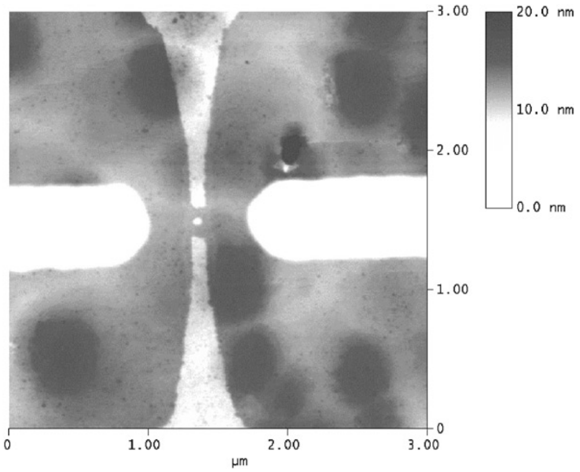

Fig. 3. Atomic force micrograph of a single electron transistor. The vertical leads are designed for the source and the drain. The dot in the middle is the island. The bias applied to the two side gates is to modulate the tunneling current passing through the quantum dot island.

widths ranging from 5 μm to 100 nm, the boundary scattering is nearly 100% specular. As a result, quantum wires maintain a long elastic mean free path and a long coherence length.

In summary, we have developed a novel technique for the fabrication of one-dimensional quantum wires. The new fabrication method utilize the different surface Fermi level pinning positions of InAs and AlSb. Once the surface material, either InAs or AlSb, is modified, the surface Fermi level and the band bending change accordingly. Although there is no metal gate defined, the up shift of the surface Fermi level pinning position in the patterned area makes the system behave as if there is a metal gate with a +0.5 V bias readily applied.

The electrons are confined in a relatively steep lateral potential. Because the induced electrons are approximately 31 nm buried below the surface, there is no excess impurity scattering by surface states. The elastic mean free path of narrow wires is the same as that for two-dimensional electrons; it is not degraded by boundary scatterings, as evidenced by the measured nearly 100% specularity. In particular, the fabricated 15 μm-long wires show long elastic mean free path ($>$ 1.4 μm) and long phase coherence length ($>$ 3 μm) at 2 K. This long characteristic transport length scale in conjunction with the short depletion length at the edges ($<$ 15 nm for each side), indicate that it is feasible to define a compact quantum circuit within the coherence length.

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